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DEVELOPMENTS IN THE USE OF RECYCLED AND SECONDARY MATERIALS IN COASTAL STRUCTURES

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Abstract
Significant developments in the UK and Europe over the last decade in the use of waste materials in coastal structures are explained. The requirements for such materials given their likely context of use are set out. Specific information is given on the application of recycled timber and secondary and recycled aggregates and the paper concludes with a more detailed case study based around the re-use of tyres.

Introduction – the challenge
In the 21st century, coastal engineers are faced with the same challenges as many other engineers and professionals in global society in seeking to deliver a more sustainable future. Sustainable development, according to the Brundtland report (WCED, 1987), is development which "meets the needs of the present without compromising the ability of future generations to meet their own needs." The UK government (DETR, 1999) states that sustainable development therefore means "meeting four objectives at the same time, in the UK and in the world as a whole:

- Social progress which recognises the needs of everyone
- Effective protection of the environment
- Prudent use of natural resources
- Maintenance of high and stable levels of economic growth and employment."

Whilst engineers can address generally in their strategies and projects the appropriate balancing of the social, environmental and economic aspects, it is in the prudent use of natural resources where they have a particularly significant role to play. The challenge for engineers is to achieve the same levels of benefit for society as is achieved at present but with the use of energy and natural resources reduced, possibly by up to a factor of 10 (Parkin, 2000).

Part of the reduction in resource use can be achieved by more effective use of mineral resources and of timber (the only 'natural' material used in coastal engineering – Perdok et al, 2003). In the UK, 89% of all waste is dumped but UK government policy is to halve this figure. The UK government has therefore started to discourage extraction and waste production by imposing taxes on resource abstraction and on waste disposal, thus encouraging the construction industry to reuse any waste they produce or seek cheaper alternatives to the primary materials they use. A further driver for change within the European Union arises from the various Waste Directives, under which disposal of some materials to landfill sites is now being completely banned and the preferred approach for dealing with all waste is to follow the waste hierarchy, i.e. in order of choice:

- Reduce
- Reclaim
- Reuse
- Recycle

Until recently, waste materials were only used where, during the normal iterative process of developing engineering options (now often known as ‘value engineering’), they were identified as being available in sufficient quantity and at a low enough price to be attractive. However, waste materials were often perceived as being of poorer quality and offering inferior performance. Whether this was actually the case is unclear. However, where failures did occur from using such materials, the causes were often that the materials were either:

- used without proper quality control or quality assurance, or
- used in solutions that were not properly engineered.

For the latter reason, such materials have sometimes re-entered the waste stream, an issue which is of particular concern today to producers. This concern arises from the legal principle of producer responsibility to deal with such uncontrolled waste, which is being applied by a wide range of governments, within the European Union and elsewhere.

In this climate new and more reliable systems and products for making use of waste materials are emerging, and this in turn is encouraging the development of new technical information and guidance to support their use.

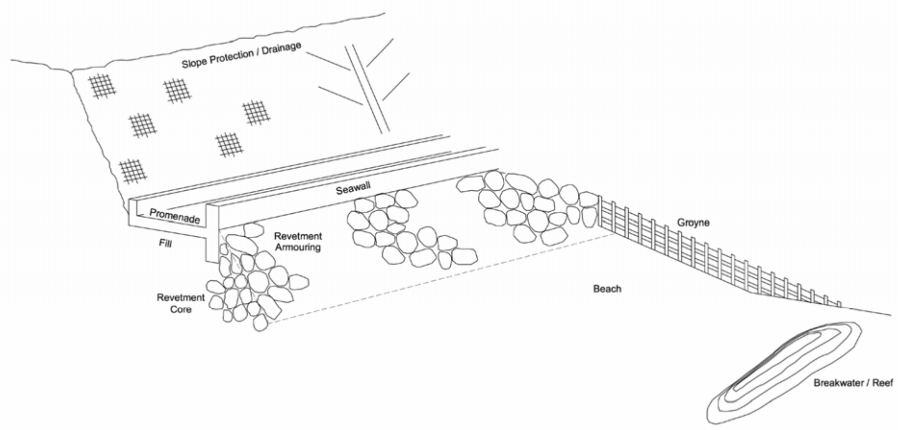

Figure 1 Typical group of coastal engineering scheme elements.

Requirements for waste materials in coastal structures

A group of typical, but idealised, coastal engineering scheme elements is shown in Figure 1. For the purposes of materials issues, these elements can be grouped into the following categories:

1. Materials used in hard defences in their own right (timber, steel or recycled equivalents) and are exposed directly to wave action.
2. Materials that are used in permanent combination with other materials, e.g. aggregates in cementitious or asphaltic concretes.
3. Granular surface layer materials (including large rock armour) that are

exposed to the direct action of waves immediately, whether in a beach or in a coastal structure.
4. Mobile beaches or structures requiring granular fill that needs to be mobile now or at some time in the future.
5. Bulk fills for beaches or coastal structures that are never exposed to the direct action of waves, although they might have some requirements (e.g. for permeability) that are associated with the fluctuation in water levels or pressures.
6. Bulk fills for containers such as geo-bags and gabions.

Of these categories, those that involve direct exposure to the action of the sea have the most onerous requirements:

- Materials in hard defences must be resistant to abrasion and to chemico-biological attack.
- Materials for use as aggregates in concretes must be able to be bound satisfactorily with the concrete matrix and be durable.
- Materials in the surface layers of rubble mound structures, including breakwaters and revetments, must be hydraulically stable and also resistant to abrasion and to chemico-biological attack, whether that attack comes now or at some time in the future.
- Materials for use as bulk fills probably have the least onerous requirements. However, there will need to be some controls on, or knowledge of, basic factors such as permeability and bulk density. As these materials may not require high densities for hydraulic stability they can potentially be of lower density than traditional materials, which may offer other design advantages.

In addition to these engineering requirements, all materials of whatever category must not leach into the water environment any chemical at any rate or concentration that would be harmful to that environment, whether instantaneously or by progressive build up in the ecosystem. The process of using any waste material may also be subject to regulatory controls, depending on the degree to which the recovery of the waste has been completed (in the view of the regulator) prior to commencement of construction.

In all cases, if secondary or recycled materials are to be used then they must be available locally in sufficient quantity and at an economic price. Waste materials used in the construction of coastal defences must also, where necessary, give performance that is comparable to that offered by traditional materials.

When comparing project options the traditional approach is to compare their engineering and environmental performance and whole life costs (see also Bradbury et al, 2003). A further form of comparison that should now be undertaken is to examine the environmental impact of the choice of materials associated with project options. A simple (MS Excel) spreadsheet tool is available (Masters, 2001) which allows engineers to use standard information on types and quantities of materials and their associated transport distances to the site of construction to compare scheme options over a range of environmental issues. For each material, a database of the environmental impacts from the life cycle stages identified above is included within the spreadsheet tool. Weighting factors developed by the UK Building Research Establishment are used to adjust the data and provide a single ‘Ecopoints’ score for each project option allowing them to be ranked.

Analyses such as ‘Ecopoints’ tend to emphasise the dominance of form and distance of transport in the environmental impact of materials selection, as well as the source of the material in the waste hierarchy (see above). The effect of this is that another kind of hierarchy can be imagined (Masters, 2001) with the following options in order of preference:

1. Suitable materials available on site from a previous scheme or structure.
2. Locally sourced reclaimed or recycled materials appropriate to fulfil the

functions identified in the functional analysis.
3. Reclaimed or recycled materials from non-local sources that can be delivered to site predominantly by sea or rail OR locally-sourced primary materials.
4. Reclaimed or recycled materials transported from non-local sources by road OR primary materials transported from non-local sources predominantly by sea or rail.
5. Primary materials transported from non-local sources by road.

Figure 2 Repairs to fire-damaged pier at Southend UK using recycled timber.

Secondary and recycled materials available for use in coastal structures

The following discussion is not an exhaustive review of potential recycled and secondary materials, but reflects by way of example the principal categories of materials listed above

Timber. There are particular environmental challenges associated with the procurement of new sustainably produced timbers, especially where, by reason of requirements for length, strength or durability, these are required to be tropical hardwoods. For a fuller discussion of this topic see Perdok et al (2003) and Crossman & Simm, (2002).

Because of these challenges, many engineers and client bodies in the UK are looking to source their timber requirements, as a matter of policy, from recycled material whenever possible. Care needs to be taken to avoid timber with an apparent recycled designation, but which is just material that has been sold on by a supplier of primary material. Genuine recycled timber will often come with evidence of previous use such as boltholes etc and may require reprocessing through a sawmill to make it suitable for re-use. Several projects have now been constructed in the UK using significant quantities of recycled timber including the repairs to the fire-damaged recreational pier at Southend, Essex, UK (see Figure 2).

Recycled and secondary aggregates have the potential to take 30% of market share for all aggregates used in England. The following definitions are widely used:

Recycled aggregates are derived from reprocessing materials previously used in construction. Examples include construction and demolition waste material and railway ballast. In the UK these are of quite widespread availability, some 94 million tonnes of construction and demolition waste being produced in England and Wales in 2001 of which some 38 million tonnes was recycled as aggregate by crushing and screening. However, the evidence from the UK is that not much is currently being used in coastal engineering projects save for a few situations where it was both cost effective and environmentally attractive to do so. These figures exclude dredged material which can be reused beneficially in various ways (Burt & Cruickshank, 1999).

Secondary aggregates are usually by-products of other industrial processes not previously used in construction. Industrial process wastes are being used extensively in concrete production local to their source. UK examples include: china clay sand (in SW England), furnace bottom ash (Fba) and pulverised flue ash (Pfa) from coal power stations; blast-furnace slag from iron manufacture and other mineral wastes; waste foundry sand and quarry wastes. Some of these uses are now well established and take advantage of the cementitious properties of some of these materials; slower setting times are offset by reduced permeability and increased durability. However, very large unused stockpiles of mine and quarry waste remain in the UK, especially of china clay waste (45-100 million tonnes), and slate waste (400-500 million tonnes).

Recycled and secondary aggregates bound in concretes. Aggregates can be used in coastal engineering in both their bound and unbound condition. The subject of aggregates bound into cementitious and asphaltic concretes is beyond the scope of this paper, but it is worth noting that there are a wide range of potential applications (see, for example, case studies at ***www.aggregain.org.uk***). These include innovative uses such as:

- The use of glass cullet as aggregate in mass concrete production. Glass cullet can also be used in asphaltic concretes.
- The use of tyre shred material in dense or porous sand or stone asphaltic concretes for coastal revetments.

Unbound recycled and secondary aggregates for use in structures and beaches. A number of the secondary aggregates listed above can be processed to produce material suitable for bulk filling and, where the quality control is suitable, potentially for underlayers to structures. Most materials can potentially be used as bulk fills so long as their permeability, grading, unit weight and durability is appropriate to the application. In all cases, care is required over any potential for harmful leachates.

In beaches, such secondary aggregates can also be considered for use in the zone of active wave action, but here the aggregate will be subject to significant abrasive forces. These abrasive forces may be a positive thing in that they will round the material and hence make it more acceptable for amenity use. On the other hand, if the rate of reduction of particle size due to abrasion is too large, then there will be a risk that the beach will sustain excessive loss of material by wave and tidal action. Edge et al (2002) cite the use of pre-rounded glass cullet in beaches.

Figure 3 Crinnis Beach, Cornwall, UK – a china clay quartz beach.

Secondary aggregates have been used on UK beaches in the past, often in an accidental way during the UK Industrial Revolution and subsequently, when deposition on the coast of arisings from industrial processes was still acceptable. Examples of beaches that remain from this kind of activity include:

- Coal beaches between Sunderland and Hartlepool and Newbiggin and Blyth in North-East England and between Kirkcaldy and Buckhaven in Fife
- Brick beaches at Sefton, North West England, arising from clearance of slums and World War II bomb damage.
- Extensive china clay quartz beaches in Cornwall as a result of the deposition of china clay waste (see example in Figure 3).

Secondary aggregates could still now be used for a conventional beach recharge, if a delay in rounding or washing of the material was acceptable. At a lower rate, they could also be used for trickle charging. Perhaps the most attractive option in the short term is to bury such fills in the rear part of the beach which is currently inactive or only active in very extreme events, in order to release the equivalent volume of naturally occurring material for placement in the active beach zone. Secondary materials could also be considered for any bulk filling operation where they will be fully contained in the future e.g. within large geotextile bags.

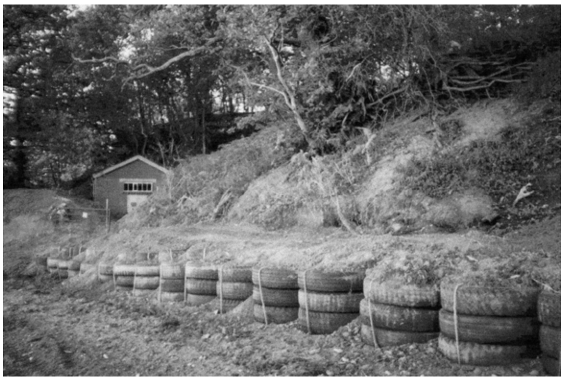

Figure 4 Linked tyres (a) for erosion protection and (b) in underwater reef

Case study – use of tyres in coastal engineering

Historical developments in the use of tyres. Tyres have been available for use in coastal structures for many years. Early uses included as simple fenders on small boats or quay walls; this practice still continues and indeed has been extended to the use of tyres to protect large pneumatic fenders. In the 1970's and 1980's, tyres started to be used in floating breakwaters, a practice which was particularly popular in the Great Lakes in North America. In the UK, the large tide ranges and aggressive wave action around our coasts meant that the effectiveness of such breakwaters was limited and durability was a major problem. A floating breakwater at Port Edgar in East Lothian, Scotland, still remains, but required the tyre rims to be filled with polystyrene foam to keep it afloat as wave action tended to remove the trapped air in the rims that was intended to keep the breakwater afloat. Other forms of structure were examined during this time such as tyre and post walls but these were inadequate to properly resist erosion behind them. A review of tyres as a form of low cost coast protection by HR Wallingford in the mid 1980s rejected them as a viable option.

In walls and embankments, both along coasts, riverbanks and roads, tied and untied honeycomb networks of tyres have been used as a kind of soil reinforcement. This option remains and indeed may be suitable in sheltered estuarine environments (see Figure 4), but is not believed to be robust enough for open coast applications. They are also subject to ongoing degradation by UV light. However, such systems have shown promise as anti-scour mattresses over offshore pipelines. Linked tyres have also been used with some effect in creating reefs on the seabed to encourage and provide habitat for marine life (see Figure 5.) The latter applications, being underwater, do not pose UV light degradation problems.

A development that has attracted recent attention is **tyre bales**. In the baling process, which originated in the USA, about 100 tyres are compressed into bales of approximate size 30"×50"×60"and locked with steel wires (Figure 5). The resultant bales weigh about 1 ton and can be used as void fillers in beaches and structures. Although the tyre material density is 1.3 t/m^3 and the degree of compression is high, the bale porosity is about 50-60% and so the bulk density of the bales is only about 0.6 t/m^3. This makes them attractive for use over soft ground.

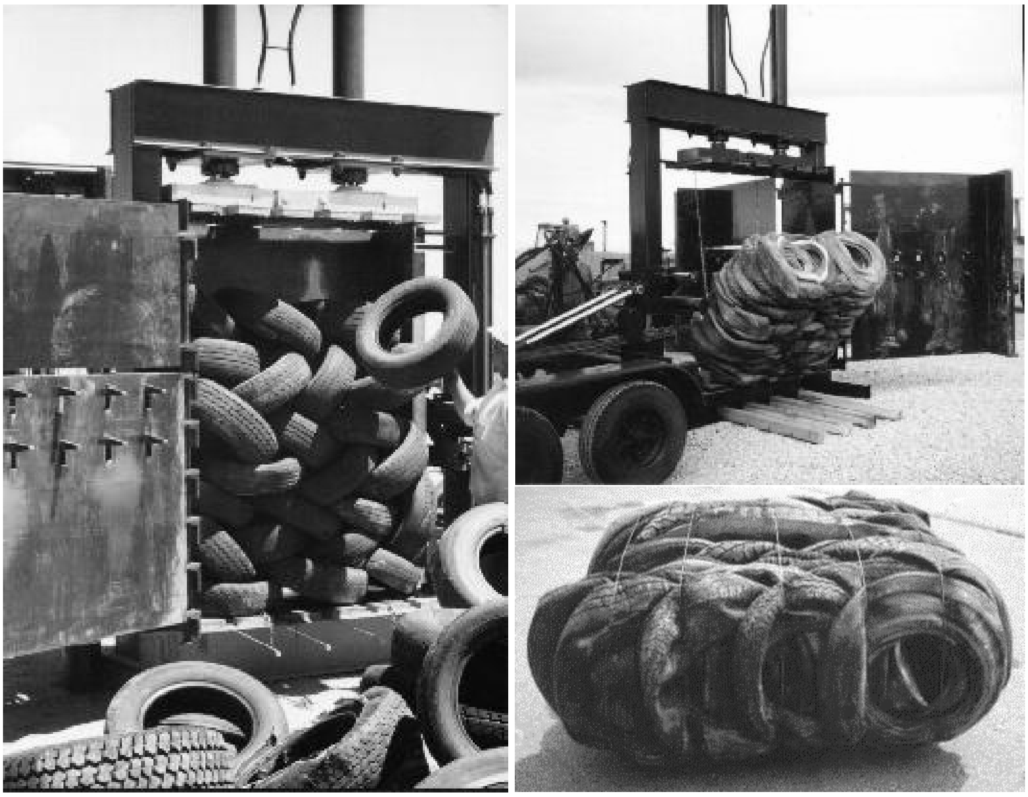

Figure 5 Tyre baling

Impact of waste regulation in Europe. Interest in new applications for used tyres, such as in bales, has been driven by changes arising from the European Waste Directives. The general disposal of whole tyres to landfill sites has been banned from July 2006 and tyre shred is similarly to be banned from 2006. Hence options for the use of tyres which involve "recovery" i.e. conversion to a new product or use, rather than disposal have become very attractive. At the same time, however, regulatory agencies are becoming more cautious about the potential environmental impact of waste materials like tyres, particularly in regard to:

- The risk of chemicals being leached from such materials at concentrations that would be harmful to the environment.
- The possibility of "sham" recovery i.e. recovery that is in fact waste disposal.
- The risk of materials that have not been properly recovered re-entering the waste stream.

A particularly important regulatory decision is when tyres or indeed any other material has been processed to a degree that it can be viewed as a finished product. The current position being adopted by the Environment Agency in England, in the light of recent decisions of the European Court, is that tyre bales legally remain waste until incorporated into an engineering structure. This view was adopted because "the essential characteristic of a waste recovery operation is that its principal objective is that the waste serves a useful purpose in replacing other materials… ."

The UK Environment Agency has therefore stated "that tyres converted into tyre blocks cannot be said to have been fully recovered at that point but will usually have been recovered once they have been put to use and are incorporated into an engineering structure." Because use of rubber and/or tyres is not an exempt activity for the purposes of the UK Waste Management Licencing Regulations 1994, it follows that Waste Management Licencing is required for each and every site at which waste is to be stored or recovered. This includes the construction sites where the bales are to be installed. The Environment Agency has sought to simplify the process of obtaining a licence for such waste recovery projects. However, it remains necessary to prepare additional documentation to secure a licence including a working plan and a risk assessment, and to have a waste management competency check on those responsible for the on-site construction operations.

Laboratory studies on tyre bales. In addition to immersion and weighing tests to determine porosity and density, tests have been carried out to assess:

- **Bale permeability**. On tests on three different bales, this was assessed to be of the order of 0.1m/s (+/- a factor of 2), i.e. roughly equivalent to that of a typical gravel. Bale permeability was assessed in a flume at HR Wallingford with all flow forced through the bales by sealing around them with builder's foam.
- **Interbale friction coefficient, μ**, was assessed to be about 0.7 based on several tests in which the load required to drag one bale over the other was measured.

These assessments were followed by scale model tests in which model tyre bale units were manufactured using rubber chip and then subjected to wave action in the flume in the usual way. The bales were shown to be highly unstable, being displaced in waves of height between 0.2 and 0.5m prototype. It was concluded that although the bale permeability at 0.1 m/s was high for steady state conditions, it was too low to allow dissipation of large transient wave-action-induced pressure gradients. Thus the bales were not very effective as porous elements for this purpose. Instead, they acted as bulk elements with a density lower than water and moved because of their buoyancy.

Pilot project – Pevensey, English south coast

A pilot project is being undertaken at Pevensey, in which 300 tyre bales have been installed in the rear of a large gravel beach. The objective is to examine the use of tyre bales for releasing the gravel which they displace in order to provide a source of material for recharging the beach face. This indigenous gravel provides an alternative to using offshore marine reserves.

The layout (see Figure 6) allows the tyres to be slowly washed by the tide and the engineering and environmental performance of the bales to be monitored. Monitoring plates to measure bale compression with time and water sampling wells to monitor water quality and leachate levels were installed as part of the pilot.

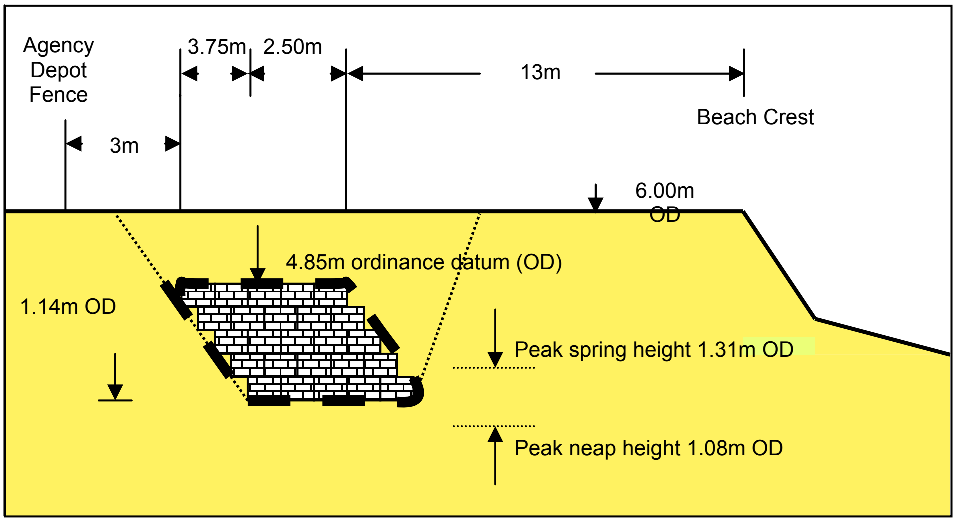

Figure 6 Layout of tyre bale installation in Pevensey beach

Figure 7 Installation of tyre bales in beach.

One part of the bale group was entirely wrapped with geotextile (Figure 7) to prevent ingress into the bales of fines from the gravel beach and the other was just wrapped with an open geogrid. The bales were then completely covered with beach material. Initial results from the physical monitoring indicate that:

- Vertical compressive strain/creep of the bales over a 12 month period is about 1%, considerably less than might have been expected.
- Other settlement and movement of the bales is negligible.

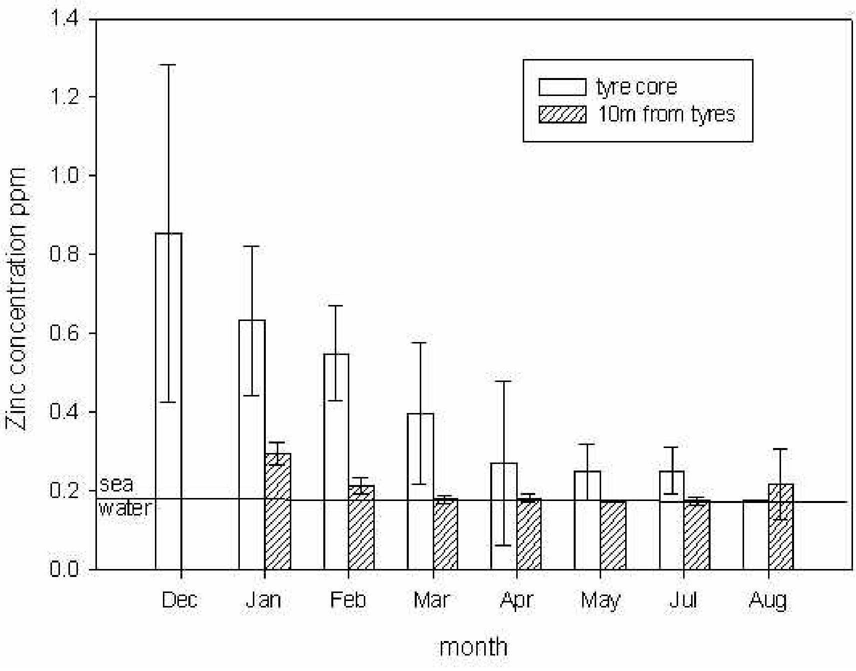

Figure 8 Average (+/- 1.0 standard deviation) zinc concentrations (corrected for salinity) in tyre core wells and in wells 10m seaward & landward of tyre block.

Environmental monitoring is ongoing and comprises monthly monitoring at peak spring tide when the bales are wetted. Measurements are made of water levels, salinity and zinc concentrations in the 8 beach wells, sea and a freshwater channel behind the beach. Water samples are being analysed for the main components of tyre leachates (zinc and benzothiazoles) and their toxicity is being compared with values for fresh and salt water. Analysis of the results is yet to be completed but Figure 8 suggests an ongoing decline in release of zinc, the main tyre tracer, down to levels comparable with those in normal seawater. This decline in release rate arises because the total amount of material that can be released is related to the previous surface degradation of the tyres by UV light and, now being covered, no further degradation can take place. As a result, it has been estimated by Collins *et al.*(1995) that a total of about 10mg of zinc can be released from one tyre. The above results suggest that there is unlikely to be a significant environmental impact from the leachates arising in such projects and is probably significantly less than that arising from runoff from tyre deposits on road surfaces. Pevensey is not the only pilot project taking place as part of the research and later papers will report on the results from the other studies.

Conclusions

Waste materials such as tyres offer very real engineering benefits to coastal structures as well as solving the problem of excessive use of natural resources and their wasteful disposal after use. However, the environmental risks (e.g. leachates) arising from the use of such materials need to be addressed. Ongoing research and pilot projects will provide the information required for engineers to use these materials successfully. Reuse of tyres offers a good illustration of these principles.

Acknowledgements

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